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INVESTIGATION OF INTEGRATED PASSIVE TECHNIQUES FOR PRESSURIZATION AND THERMAL CONTROL IN A SPACE WORKER'S GARMENT

TECHNICAL DOCUMENTARY REPORT AMRL-TDR-63-21
March 1963

Life Support Systems Laboratory
6570th Aerospace Medical Research Laboratories
Aerospace Medical Division
Wright-Patterson Air Force Base, Ohio

Contract Monitor; Lt. Robert F. Witte
Project No. 6301, Task No. 630104

(Prepared under Contract No. AF 33(657)-8095
by A. L. Marcum and H. A. Mauch of the
Mauch Laboratories, Inc., Dayton, Ohio)

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FOREWORD

This is the final Technical Report on the work performed under Contract No. AF 33(657)-8095 from 1 February 1962 to 31 January 1963 by Mauch Laboratories, Inc. Dayton, Ohio. The work was sponsored by the Life Support Systems Laboratory, 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The contract was administered by the Altitude Protection Section of the Life Support Systems Laboratory under Project Number 6301 "Aerospace Systems Personnel Protection," Task No. 630104, "Space Protective Garment." Lt. Robert F. Witte of the Altitude Protection Section monitored the contract for 6570th Aerospace Medical Research Laboratories. Mr. H.A. Mauch was the principle investigator for Mauch Laboratories, Inc.

This report contains design and performance information on garments for Aerospace personnel protection. Since the release of such information would be prejudicial to the best interests of the United States of America, this report has been classified CONFIDENTIAL.

ABSTRACT

The purpose of the work described in this report was the investigation of integrated passive techniques for pressurization and thermal control in a space worker's garment. The specific goal of this work was the development and fabrication of a complete laboratory model space worker's garment, based upon passive techniques, with which the problems of passive physiological protection could be further explored. The suit design which developed is based upon mechanical pressurization using an expandable closed cell foam material as the pressurizing medium, and upon thermal control by the controlled evaporation of sweat at reduced pressures. Two experimental components, an arm section, and a single leg section, were assembled and tested to provide data for the design of the suit. The results of the investigation indicate that the PAPRETEC (PAssive PREssurization and TEmperature Control) concept is feasible and that further development of the suit should be undertaken.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Wayne H. McCandless

WAYNE H. McCANDLESS
Chief, Life Support Systems
Laboratory

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I INTRODUCTION

A. GENERAL

This report describes an investigation of integrated passive techniques for pressurization and thermal control in a space worker's garment which was carried out by Mauch Laboratories, Inc. The objectives of this investigation were the development of a space worker's garment based upon passive methods of physiological protection, and the investigation of evaporative cooling as a means of thermal control in a space suit.

The design objectives established for the space worker's garment may be summarized as follows.

1. The design of the suit must be as simple as possible, consistent with reliability, comfort, and ease of donning.

2. The method of pressurization, and of thermal control must be independent of auxiliary systems.

3. The suit must apply a pressure of 3.5 psi uniformly over the body when worn under space conditions with a breathing pressure of 3.5 psia. The comfort and mobility of the suit under these conditions must be such as to allow the suit to be worn for a minimum of two hours.

4. In an ambient pressure of 5 psia, the comfort and mobility of the suit must be such that it can be worn for an indefinite period. Furthermore, the suit must permit 4 hours of wear in the laboratory under conditions of temperature and pressure ranging from 50° F to 120° F and from 14.7 psia to high vacuum.

5. Provisions for urinary relief must be incorporated into the suit.

B. BACKGROUND

In an earlier investigation by Mauch Laboratories, Inc. into the problems of passive physiological protection for space workers, a suit design was proposed in which pressurization was to be achieved mechanically by enclosing the body in a restraining garment which would not permit the body to expand under the influence of high internal pressures and in which thermal control was to be achieved by the controlled evaporation of sweat at reduced pressures. The reduction of this concept to practice is described in detail in reference 1.

(Conf) The garment which evolved during the above investigation consisted of two major components: an outer restraint garment which provided mechanical pressurization, and an airtight inner garment which served both to distribute the pressure of the restraint garment and to isolate the body from the environment so that the evaporation of sweat could be controlled.

(Conf) The restraint garment (outer cover) was made of a special material, described in reference 1. Zippers were incorporated into the cover to facilitate donning and doffing, and elastic laces were provided for controlled expansion and to allow minor adjustments to be made in the fit of the garment.

(Conf) The inner garment (inner cover) was a multilayer assembly consisting of a lining of knitted fleece, a layer of varying thickness of a soft and incompressible filler compound, and an outer impermeable layer of neoprene rubber. The primary function of the fleece lining was to facilitate the movement of water vapor to a series of collection manifolds so that it could be removed from the interior of the garment. The filler material was used to fill out non-circular sections of the body to a circular cross section to provide a uniform pressure at all points, while the outer layer of neoprene functioned as a vapor barrier to prevent the uncontrolled evaporation of sweat.

(Conf) The results of the tests of the several suit components which were fabricated to evaluate this design may be summed up as follows:

1. The feasibility of passive mechanical pressurization was demonstrated.

2. Although tests of the evaporative cooling principle were not conclusive, the indications were favorable.

3. Because of the thickness of the filler required in some areas, the inner covers were difficult to don and doff and were excessively heavy and stiff.

(Conf) In the light of the design objectives previously listed, the basic design concept just described contains in principle all the necessary elements, but in practice the shortcoming noted in 3. above would seriously limit the usefulness of such a garment.

(Conf) To overcome this shortcoming while retaining the desirable features of the existing design, we proposed that development continue along the lines already established except that the incompressible filler, which was responsible for the stiffness and excessive weight of the previous test components be replaced by a special, highly expandable closed cell foam. Given a foam having the correct physical properties, a suit could be designed in which the foam, by expanding in response to decreasing ambient pressure would fill the space between the restraint garment and the body and would exert exactly the required counterpressure under space conditions. Under the conditions normally present in the cabin of a spacecraft, the suit would fit the wearer loosely but it would react instantly to a loss of cabin pressure. In addition to being very comfortable, the loose fit of the suit under cabin conditions might allow a choice of methods of thermal control, including the circulation of air through the suit.

(Conf) Such a foam material would be relatively light in weight, and would be flexible and easily stretched so that it would not interfere with donning and doffing.

II DEVELOPMENT PROGRAM

A. GENERAL

The development program covered by this report was carried out in two phases. The first phase, lasting four months, was devoted to a design study and to the development of methods of manufacturing the foam pressurization material. The second phase was devoted to designing, assembling, and testing two experimental components, an arm section, and a leg section; and the complete PAPRETEC (PAssive PREssurization and TEmperature Control) suit.

B. DESIGN STUDY

1. Preliminary Design

Having established the design philosophy for the space worker's garment, we shall now describe the design of the suit in more detail, starting with those features which are based upon previous work.

(Conf) Consider first the breakdown of the suit into its major components. We have found it advantageous in the past to make this separation on the basis of function so that the garment is divided into a restraining element and a sealing element. This separation of the restraining and sealing functions eliminates any need for pressure sealing zippers, which are rather stiff and bulky and generally hard to operate because of internal friction.

(Conf) In our previous design the sealing element, or inner cover, contained a knitted fleece liner which allowed the water vapor to move freely over the surface of the body. This liner is still required but in the present case it was decided to use a separate rather than an integral liner. This will be advantageous from the standpoint of donning and doffing and will also allow the liner to be more easily cleaned.

(Conf) These major components; the restraint garment, the inner cover, and the liner , must be divided still further to provide for donning and doffing and for adjustment. Before this division can be made we must first decide upon the placement of the foam pressurization layer.

(Conf) The foam may be attached to the inside of the outer cover or it may be attached to either side of the inner cover. In each of these three cases, the inner cover may be either a snug or a loose fit; so that there are six combinations to consider. Conceivably more than one combination might be used in the same suit, but this is a condition which would be limited to very specific locations, and which for the present, will be ignored.

(Conf) Consider first the combinations in which the foam is attached to the inner side of the inner cover. If the inner cover were a snug fit, then the foam layer attached to it would tend to make it less stretchable and more difficult to don and, in addition, the restraining effect of the cover would reduce the available expansion of the foam.

(Conf) If the inner cover were a loose fit, the donning problem would be reduced and a space would be created inside the cover through which cooling air could be circulated. This space, however, would make the use of evaporative cooling in the spacecraft cabin problematical because the cover would then collapse against the body in large wrinkles which would probably become uncomfortable in time.

(Conf) The remaining combinations, in which the foam is attached to the inside of the outer cover, are more promising. If, in this case, the inner cover is a snug fit, then evaporative cooling can be used under all conditions. On the other hand, if the inner cover is a loose fit, it will be easier to don, but, unless it is made from some very thin material, we have again the problem of the uncomfortable wrinkles.

(Conf) On the assumption that a suitable material for the inner cover could be found, this last configuration: foam attached to the outer cover and a loose fitting inner cover, was selected for the suit.

Next, consider the breakdown of the suit from the standpoint of donning and doffing.

(Conf) The liner can be made either as a one piece garment with a vertical opening or as a two piece suit with a circumferential joint near the waist. Either style can be donned with comparative ease, but a vertical opening would require some form of fastener or tie while a circumferential overlap would not.

(Conf) As with the liner, the most natural and convenient division of the inner cover would be into an upper and a lower half with a simple fold over seal at the waist. To further facilitate donning and doffing, it would be advisable to make the hand covers detachable.

(Conf) The outer cover presents a more complex problem, because the location of the closure influences not only the ease with which the cover may be donned but also the mobility of the garment.

(Conf) From the standpoint of mobility, the major problem stems from the fact that a zipper cannot stretch, and cannot shorten except by becoming wavy or wrinkled. The restraint material, by contrast, must be allowed to stretch and to shrink in certain directions with as little restriction as possible if it is to function properly. To minimize the interference of the zipper with the functioning of the cover, the zipper must be oriented so that it runs in a direction in which the restraint material does not stretch.

With respect to ease of donning and doffing, the zipper should not run through areas which cannot easily be reached by the person donning the suit. This would rule out, for example, a circumferential zipper around the waist since it would be difficult due to the slack to close the zipper without guiding both chains into the slide by hand. A further objection to a circumferential zipper is that it would be impossible to adjust the fit of the suit's circumference in the area of the zipper because of its fixed length.

(Conf) With these limitations, and considering the orientation of the restraint material around the trunk, the most logical routing would be to run the zipper diagonally downward, parallel with one set of reinforcing fibers, from the neck opening to the side seam, and then turn and run parallel with the second set of fibers as far as necessary to permit the garment to be donned easily.

(Conf) In addition to the torso zipper, zippers will be required along the arms and legs of the cover. These zippers must follow the neutral line (line of constant length) of the limb to minimize their effect on mobility.

(Conf) To allow minor adjustments to be made in the fit of the outer cover, past practice has been to lace the cover together along a neutral line with a special elastic lacing, which served the additional purpose of preventing momentary overloads in the cover when a limb was flexed rapidly (see ref. 1). Laces will also be required in the suit now under consideration, but only for adjustment. The compressibility of the foam will make the use of an elastic lacing unnecessary. In order that the laces may be continuous, they will run along the outside of each leg and along the side of the torso to the arm pit and then along the arm opposite the zipper to the end of the cover. On previous units, a conventional loop tape of the type used on Air Force capstan suits was used to hold the lacing; however, if such a non-stretchable tape were used along the side of the body, it would seriously restrict the mobility of that portion of the suit. To avoid this undesirable condition, a special, stretchable loop tape is required. A description of a tape which meets this requirement is given in a later section of this report.

(Conf) Another feature based upon past experience is the use of a contoured fiberglas shell in the crotch and lower abdominal area to reduce the amount of filler required in that part of the suit. A similar shell is shown in reference 1 in the section dealing with the double leg section.

(Conf) A final problem is the design of the outer cover, and one for which no precedent exists, is the design of the shoulder. Fortunately, it appears that the combined characteristics of the restraint material and the foam filler may allow a relatively simple solution of this problem.

(Conf) The natural orientation of the restraint material in the neighborhood of the shoulder is very nearly optimum for movements of the shoulder girdle; likewise, the orientation of the restraint material around the upper arm is good for most of the movements of the arm, provided the neutral position of the arm is near midrange. The problem then, is to design the intersection of the chest cover and the arm cover so that full advantage is taken of this condition. The best approach seems to be to surround the shoulder with a spherical cover, centered approximately on the joint and supplied with break lines to cause controlled creasing during extremes of movement.

(Conf) At the beginning of the program, it was suggested that the compressibility of the foam around the chest might make the use of a chest bladder unnecessary. Early tests indicated that, if the amount of foam around the chest were such that the internal and external pressures balanced when half the tidal volume had been inspired, then the equivalent of +4 to -4 inches of

water would have to be overcome during the breathing cycle. As an alternative, the foam could be so proportioned that the equivalent pressure range would be +7 to -1 inches of water. Although both these conditions are physiologically permissible, they are considered undesirable for long term use: the second because it requires more than the normal effort for the breathing cycle; the first because of its similarity, during part of the cycle, to the partial immersion of the body in water. This condition is known to produce diuresis and other physiological disturbances and until the similarity has been investigated more fully, we feel that a chest bladder should be used. Fortunately, the incorporation of a bladder will not compromise the invulnerability of the suit since it can be isolated from the remainder of the system if it is damaged. While the bladder is isolated, the wearer will experience a condition approximating conventional pressure breathing with a mask.

(Conf) The bladder might be incorporated into either the inner cover or the outer cover although, from the standpoint of convenience, the outer cover appears to be the best location since the problem of threading a connection through a hole in the outer cover while the cover is being donned is avoided.

2. Materials

a. Foam Filler Material

(Conf) An analysis of the function of the foam layer in the suit shows that the principle characteristic desired in the foam is a high expansion ratio. This is not a necessity for the operation of the suit, since the foam layer may be proportioned to allow for any degree of expansion, but it is highly desirable from a practical standpoint for two reasons: first, because the higher the expansion ratio, the more loosely the suit can be made to fit at cabin pressure, and second, because the higher the ratio, the lower the "spring constant" of the foam. This means that the small changes in the volume of the outer cover which result when some part of the body is flexed will result in less apparent pressure changes as the expansion ratio increases.

To achieve the highest possible expansion in a given foam material requires first that the material have a low density before expansion, and second, that the restraining influence of the cell walls be reduced as much as possible.

Commercially available rubber sponges and flexible closed cell plastic foams show very little expansion as the ambient pressure is reduced because the cell walls will not stretch appreciably. Two courses of action may be taken to correct this condition: we may either modify a given base material by the addition of softeners and plasticizers or we may modify the foam physically so the cells have a large potential volume in relation to the amount of gas they contain. In this condition, the cell walls would be slack and possibly wrinkled. Within limits, the expansion of the gas in the cells of such a foam would be relatively unrestricted until the slack had been taken up in the cell walls.

Considering the first approach, it appears that the use of plasticizers in larger amounts than are normally used will not sufficiently improve the situation. Furthermore, the tendency of most plasticizers to leach out and to volatilize at low pressures makes strict dependence upon them a questionable approach.

As to the second approach, there appear to be a number of ways by which it might be possible to modify a foam structure as described. For example, it might be possible to perform the initial expansion of the foam at reduced pressures so that the cells would be larger than normal, or it might be possible to post-treat a foam material by softening it and expanding it further in a vacuum. Before pursuing either line further, it will be necessary to consider the materials and the processes which are available.

There are two processes which are in general use for the production of closed cell materials. In one method, which is used primarily for the production of rubber sponge, the base material is treated with nitrogen at high pressure so that a small amount of the nitrogen dissolves in it. The material is then heated at normal pressure to cure it and to drive the nitrogen out of solution to form cells in the cured material. The second general method is to mix into the base material, a chemical which can be decomposed, either by heat or by chemical action, into a gas which will fill the cells of the material.

Obviously, because of the specialized high pressure equipment required, the first method is not easily adaptable to our needs but the second method includes a wide variety of materials and processes which are readily modified and for which relatively simple equipment is required.

In the selection of the base material, from the standpoint of function, there are two important factors to be considered. One of these is, of course, flexibility; the other is the permeability of the material to the enclosed gas. Obviously, the permeability should be as low as possible. From the standpoint of manufacturing, because of the problems involved in heating materials in a vacuum, those materials which may be processed at room temperature would be preferred.

As the first step in the development of the foam, a survey was made to determine what materials were commercially available, both as finished products and as raw materials. From the group of finished products, several vinyl based products were selected for post-treatment studies, while from the raw materials, a room temperature curing polysulfide rubber sponge was selected for vacuum processing. The polysulfide rubber was particularly interesting because of its very low permeability. Tests of the polysulfide rubber and the vinyl foams were carried out concurrently.

Attempts to expand the polysulfide rubber sponge in a vacuum were disappointing. The vacuum processed material contained a high percentage of open cells and was rather easily torn. Further investigation of the vacuum processing method led to the conclusion that it would be very

difficult to obtain consistently uniform closed cell material by this method, and in view of the good results being obtained with the post-treatment method, work on vacuum processing was stopped.

The preliminary tests of the vinyl foams were carried out by heating the samples in a bell jar with radiant heat while the pressure in the jar was reduced to approximately 1 psia. The tests indicated that the post-expansion treatment method was feasible. The tests also indicated that materials which contained an elastomer such as nitril rubber in addition to the vinyl were superior to those which reportedly contained only vinyl in that they consistently gave a higher total expansion. Accordingly, additional samples of vinyl-rubber compounds were procured for testing.

The second series of samples were processed in an aluminum vacuum chamber which was heated in an oven. With this equipment, temperature could be more accurately controlled, and larger samples (approximately 4 x 4 inches) could be processed than had been the case in the bell jar.

Tests with the larger samples indicated that for practical purposes, a total expansion of approximately five times the original volume was the maximum which could be achieved with the materials being tested but that the volume was approximately proportional up to pressure ratios near 4 to 1.

On the basis of these tests, a material was selected for further development for use in the suit. The material, a proprietary product of the Rubatex Division of Great American Industries Inc. has a butyl rubber base.

(Conf) As has been pointed out, one of the problems associated with the use of foam at reduced pressures is the loss of gas from the cells by diffusion. In the suit, an excessive loss of gas from the foam would result in blood pooling. Consequently, the loss must be prevented or held within acceptable limits. As a design limit, a maximum volume loss of 7% in 100 hours of operation in a space environment has been set. This corresponds roughly to a volume increase of 250 cc in an "average" man with a body area of 1.9 m^2. Since this volume increase is based upon the whole body area while pooling occurs only in the limbs, it is felt that this is a conservative limit. At the end of the 100 hour period, the suit would be re-adjusted by tightening the laces and it would then be ready for another period of use.

The loss of gas from the foam can be reduced by coating the surface of the foam with a material having a low permeability. Another method is to let the material outgas until the surface cells have sufficiently collapsed to form a multilayered skin and the rate of diffusion has dropped to an acceptable level. Actually, a combination of these methods seems to give the best results.

For the coating material, Hypalon rubber has been selected because of its excellent combination of properties, including low permeability, good abrasion resistance and ease of application. Tests of a .004 inch coat of Hypalon on foam which had been outgassed for four hours showed a volume loss of less than 2% in 25 hours, based upon a sample thickness of approximately .125 inch.

The material used in the experimental components, and in the suit, was made in a vacuum chamber which was formed by clamping a square aluminum frame, 18 inches square by 1.5 inches high, between the platens of a hydraulic press. The press platens were electrically heated and water cooled and close control of temperature was possible. In use, the foam to be treated was cut to size and placed in the frame between the pre-heated platens. The press was then closed, with sufficient pressure to form a seal between the platens and the frame, and the material was allowed to soak until the temperature was uniform throughout. As soon as a uniform temperature had been established, the pressure in the chamber was reduced to below 1 psia, and the platens were cooled. When the foam had become cool throughout, the pressure in the chamber was increased to normal and the material was removed. The maximum temperature used in the process was 350° F.

b. Stretchable Loop Tape

The stretchable loop tape, which has been mentioned previously, is similar to the conventional loop tape used on Air Force partial pressure suits except that it is made with a warp of continuous multi-filament nylon "stretch yarn" rather than the regular non-stretch yarn. The tape will elongate approximately 20% under moderate loads.

c. Special Restraint Material

In the past, the individual pieces of the outer covers of the experimental components have been cut from flat sheets of restraint material. Naturally, it is difficult to cover curved forms with the flat material unless small pieces are used. Since each seam in the outer cover results in some loss of mobility, any change which reduces the number of seams is highly desirable. Accordingly, a preliminary study of methods of manufacturing the restraint material in three-dimensional shapes was undertaken.

In the manufacture of the flat restraint material, two separate sheets of neoprene rubber with imbedded Fortisan fibers are bonded together under heat and pressure (see ref. 1). It was found that, with care, these separate sheets could be laid up by hand on plaster forms and cured without pressure, and several sample pieces were made in this way for evaluation in the suit. Of course, the hand lay-up method is not suitable for quantity production of this material, but there appear to be other methods, filament winding for example, that could be adapted for the purpose.

3. Design Description

(Conf) Figures 1 through 8 show the important features of the PAPRETEC suit. With certain exceptions which will be discussed as they are introduced, the materials and the manufacturing techniques involved have been described in reference 1 and will not be described here.

(Conf) The outward appearance of the suit is shown in figure 1. A standard MA-2 helmet and boots of the type worn with the MC-2 suit are worn with the PAPRETEC suit. The helmet tie down is a simple, adjustable, web strap running from front to back through the crotch and held loosely in place by loops attached to the suit; a design very similar to that used on conventional partial pressure suits.

(Conf) Figure 2 shows the suit in its neutral position. This position is such that the major body joints are in approximately the middle of their normal range of movement.

(Conf) The suit consists of an outer cover, or restraint garment made of the reinforced neoprene restraint material described in reference 1; an inner cover or vapor barrier made of polyester film (Mylar); and a liner of knitted nylon fleece.

(Conf) The outer cover, figures 3 and 4 , is a one piece coverall-like garment, which extends from the neck to the ankles and to the hands but does not cover the fingers. Access for donning is provided by a zipper opening in front, and by zippers along the arms and legs. The cover is laced together on each body side along the trunk and legs and along the arms to allow small changes to be made in the fit. The inner surface of the garment is covered with a layer of foam filler material. A chest bladder is attached to the inside of the cover. Openings through the cover are provided for connection of a urinal line and the vapor exhaust lines.

(Conf) The front zipper runs from the neck opening, diagonally downward to the right until it approaches the lacing along the right body side. It then turns and runs diagonally to the left until it reaches the intersection of the leg cover and the trunk cover. This zipper closes toward the neck.

(Conf) On the arm, the zipper starts at a point approximately four inches above the elbow and follows the neutral line of the arm to the thumb. The zipper closes toward the thumb.

(Conf) The leg zipper follows the medial neutral line of the leg from the crotch to the ankle and closes toward the ankle.

(Conf) The lacing extends in an unbroken line from the ankle to the hand, running along the outside of the leg and the side of the trunk to the arm pit and from the arm pit to the end of the cover along the line opposite the zipper. A special stretchable loop tape, described in the preceding section, is cemented to the cover along the path of the lacing. The laces are the conventional braided type, made of nylon.

(Conf) Local stiffening reinforcement is built into the cover in the crotch and lower trunk area and in the palm of the hands to reduce the amount of foam required in those areas. In the crotch and lower trunk area this reinforcement is a thin, contoured shell of fiberglas reinforced epoxy, partially covering the lower abdomen and lower back, and extending through the crotch. A similar shell is shown in reference 1 in the section describing the double leg section. The palm reinforcement is made of stainless steel sheet.

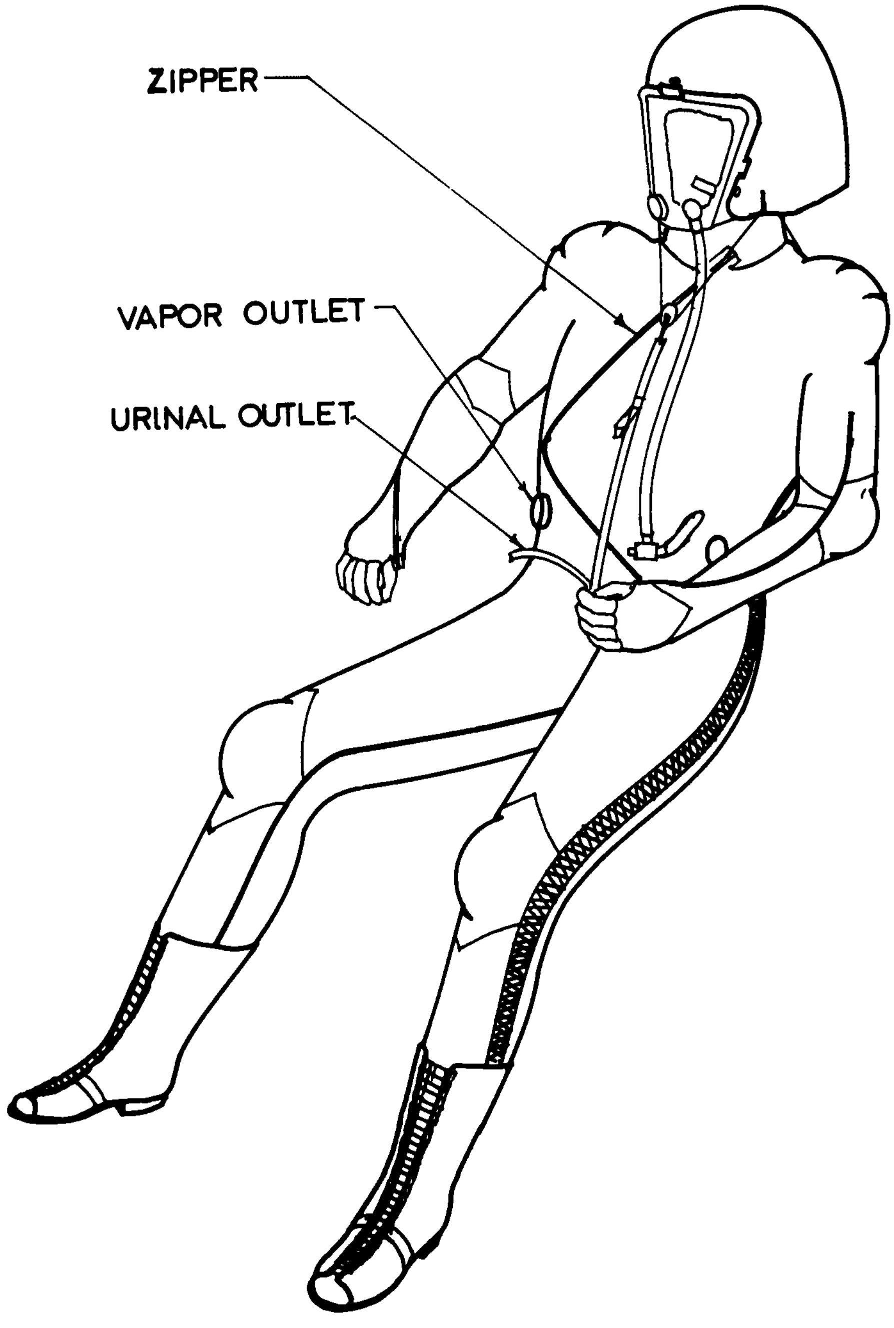


Figure 1. Complete Suit

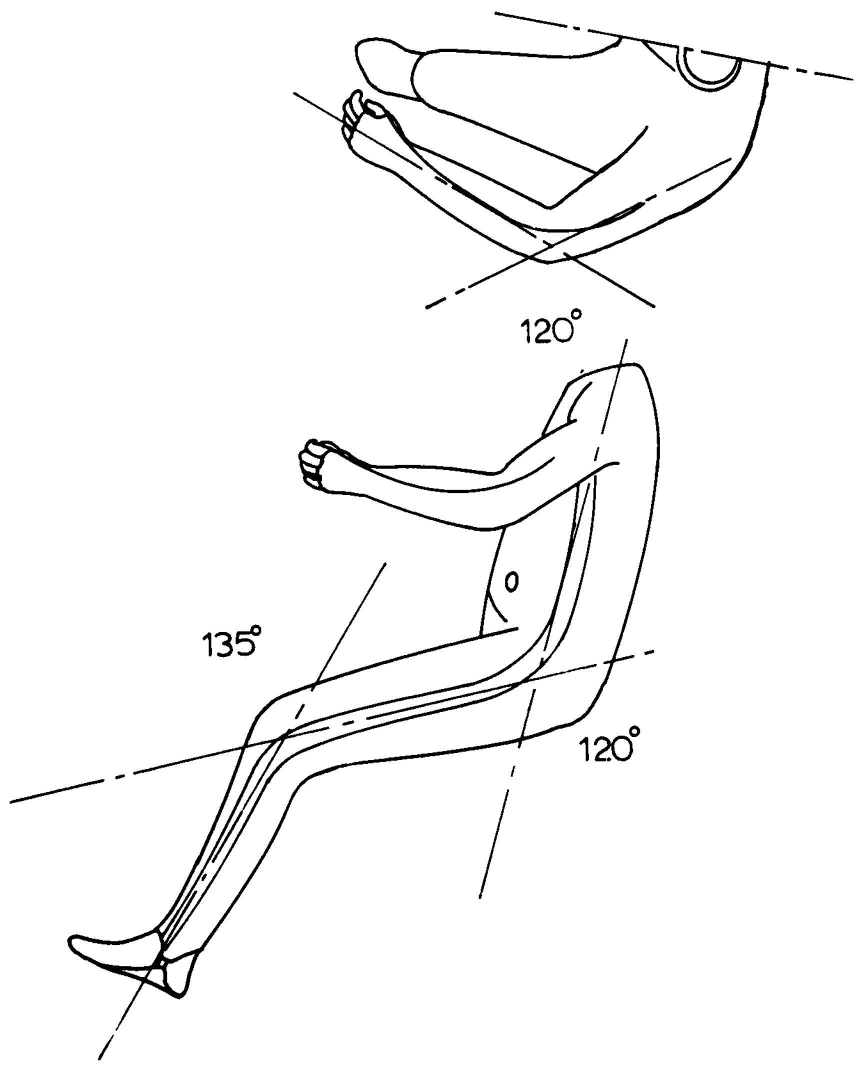


Figure 2. Suit in Neutral Position

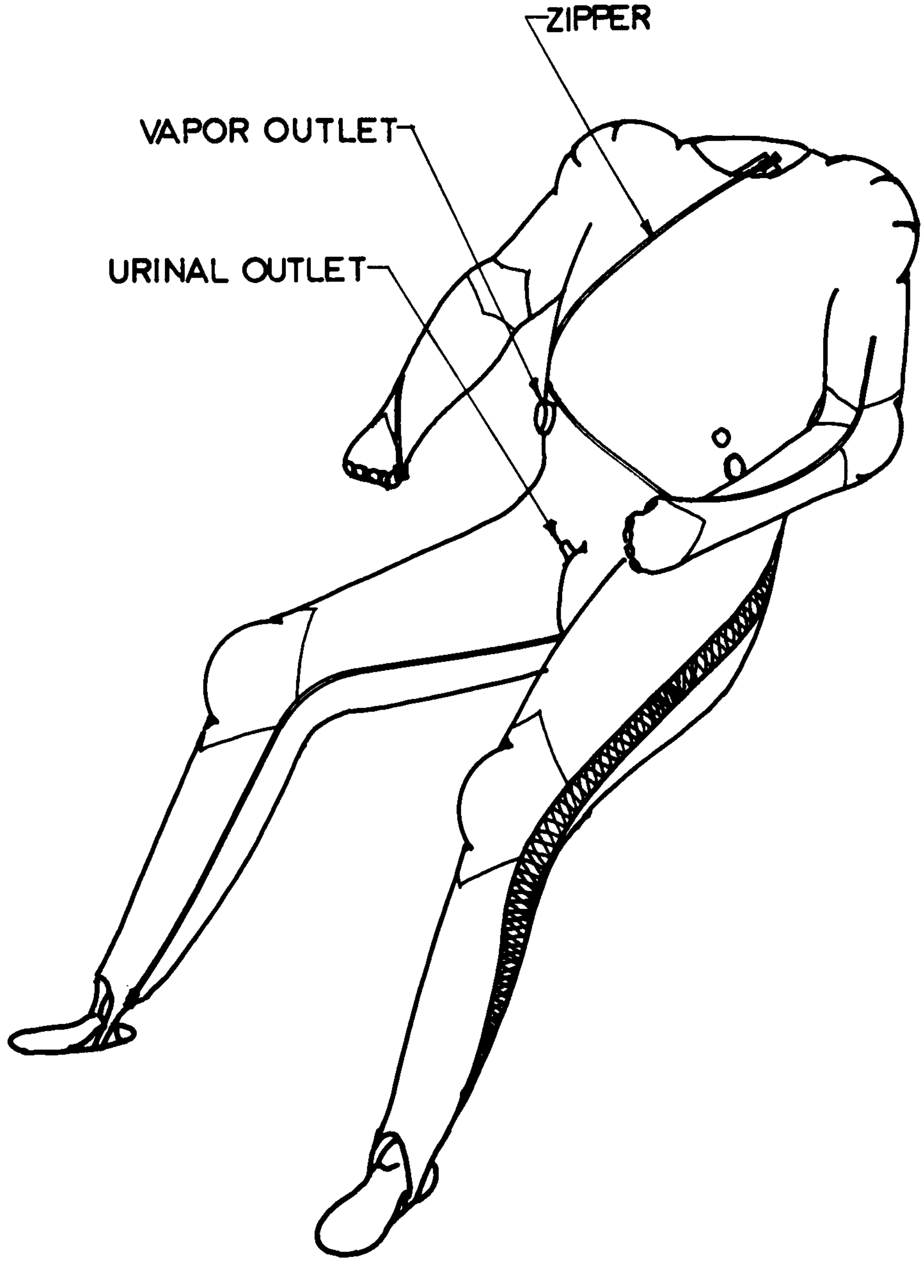
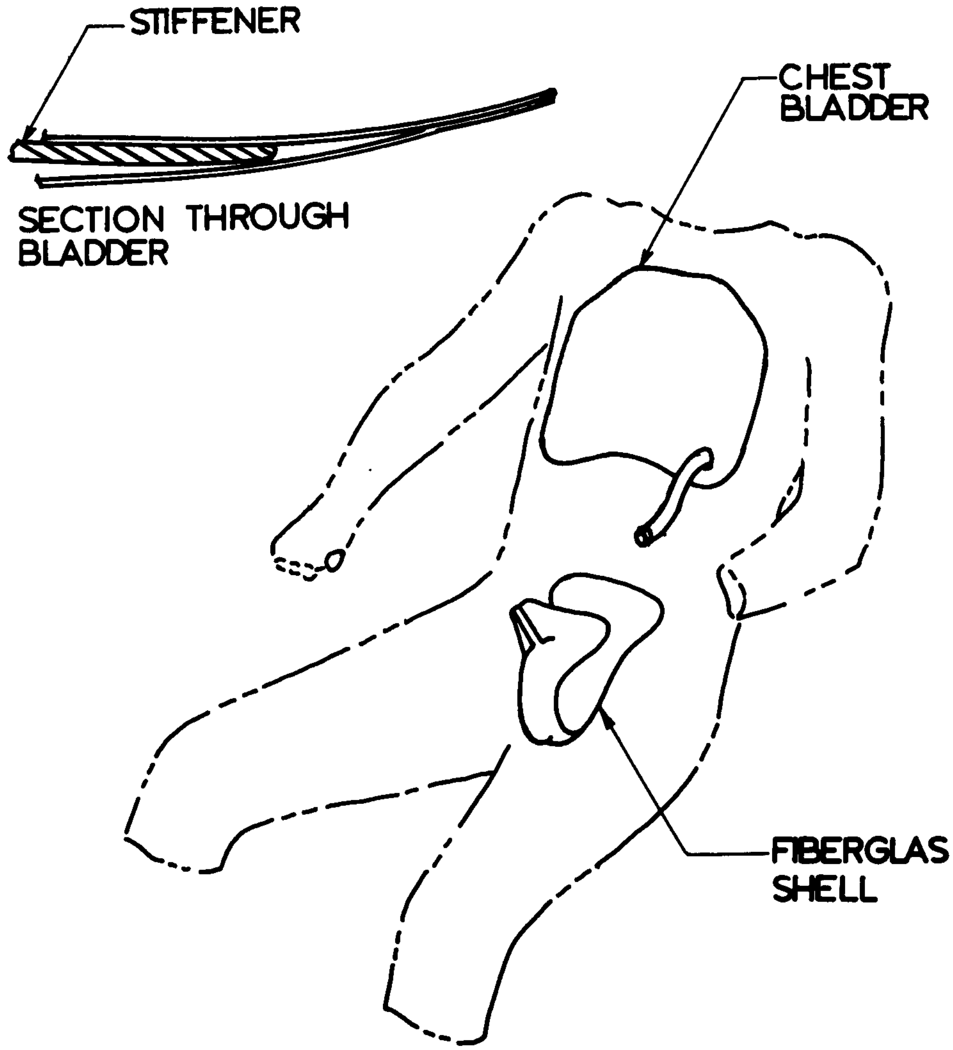


Figure 3. Outer Cover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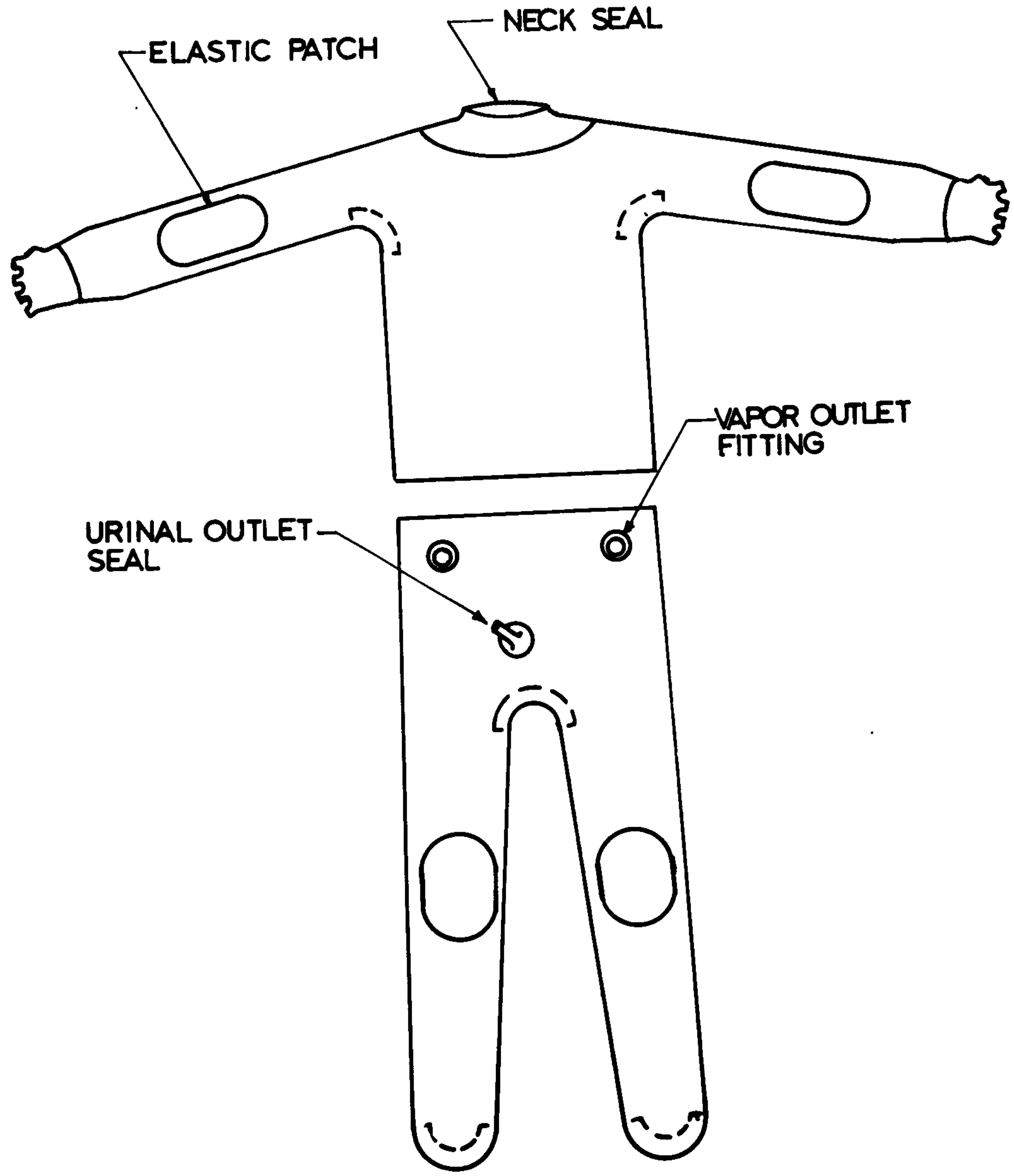


Figure 5. Inner Cover

(Conf) The layer of foam completely covers the inner surface of the cover. The thickness of the layer varies from point to point in proportion to the desired space between the body and the outer cover, and is such that at an ambient pressure of 3.5 psia, the foam just makes contact with all points of the body. The exposed surface of the foam is coated with a layer of Hypalon rubber to minimize the loss of gas from the cells when the suit is worn at reduced pressures.

(Conf) The chest bladder lies between the foam layer and the inner cover and is attached to the outer cover at two points on the left side, one point of attachment being the inlet connection near the waist. A stiffener is installed inside the bladder to keep it from wrinkling when it is not pressurized.

(Conf) The inner cover, figure 5, is a loose fitting suit of Mylar film and is made up of a trouser-like lower half and a pullover-like upper half. A neck seal is permanently attached to the upper half while the hand covers are separate. The upper and lower halves overlap at the waist and are folded together to form a seal.

(Conf) Fittings for the attachment of the vapor exhaust lines are installed in the lower half of the cover. These fittings line up with openings in the outer cover.

(Conf) Mylar was selected for this application because of its excellent combination of physical properties which include both high strength and good fatigue resistance.

(Conf) The knitted nylon fleece liner is a two piece suit consisting of an upper and a lower half which overlap at the waist. The lower half completely covers the lower half of the body including the feet, while the upper half extends only to the base of the fingers and to a line around the neck. A minimum restriction to body movements is achieved by orienting the fleece so that its maximum stretchability lies in the proper direction.

(Conf) To facilitate the removal of water vapor from the extremities, a manifold system made of "Trilok" three-dimensional fabric is attached to the liner as shown in figure 6. The manifold follows the path of the lacing in the outer cover and serves to distribute local pressure variations caused by the lacing.

(Conf) Nylon fleece was selected in preference to the cotton fleece used in the past, because it resists "pilling" and because it has a finer structure and is more stretchable than cotton fleece. The fact that the nylon fleece does not absorb moisture as cotton fleece does may also prove to be an advantage since it will retain most of its insulating value if the surface of the skin should become damp, while under the same conditions, the insulating value of the cotton fleece would decrease considerably. Normally, the skin will not be covered by a film of sweat although, in a hot environment, some areas of the body may become wet.

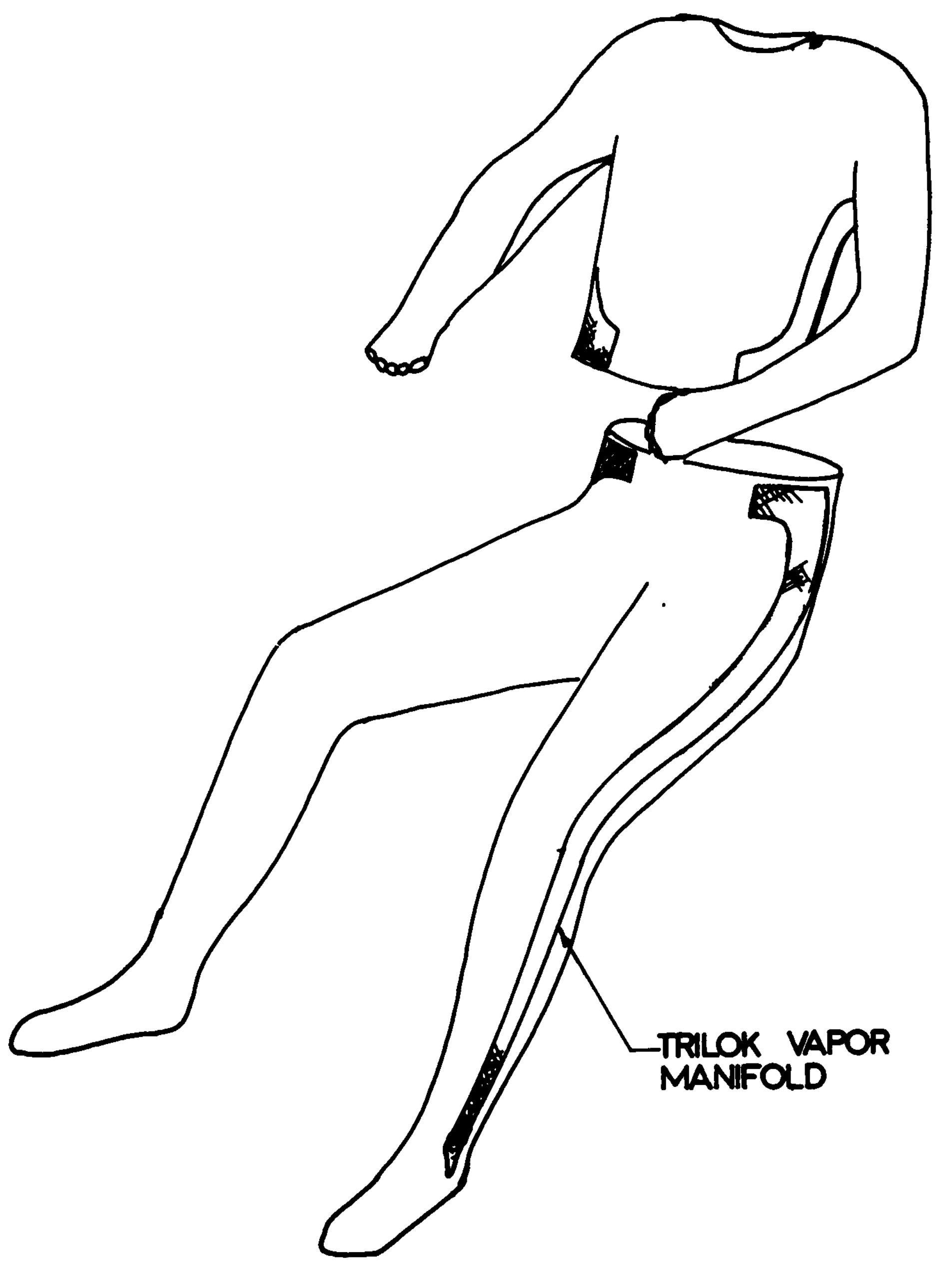
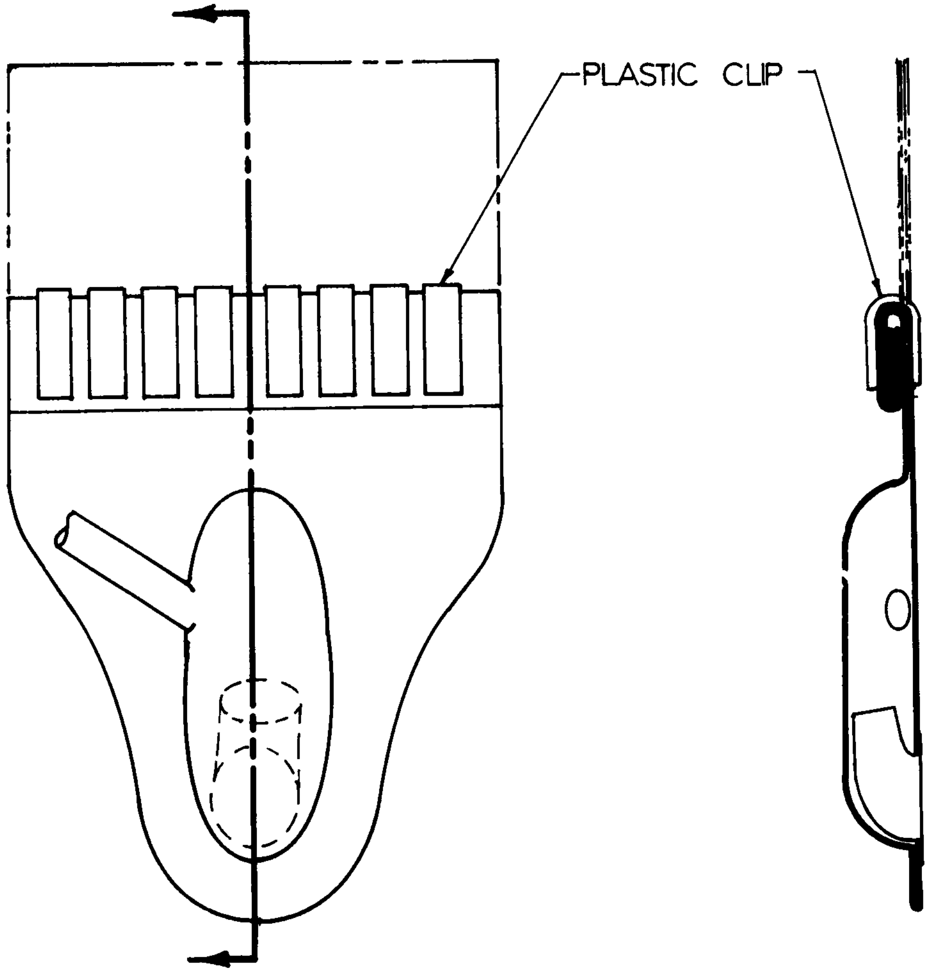


Figure 6. Liner


PLASTIC CLIP

(Conf) Since the urinal unit, shown in figure 7, lies between the fiberglas shell and the body, the bulk of the unit must be kept as small as possible, consistent with the requirement for easy donning. The design shown is thin to avoid pressure points but the urinal can be opened to facilitate donning.

C. FABRICATION OF TEST UNITS

1. General

(Conf) With the above design description as a guide, two experimental components, an arm section and a single leg section, were fabricated and tested before the design and fabrication of the complete suit was undertaken. In general, the tests of the experimental components showed that the basic design was sound and no significant change was made in the original design when the suit was assembled.

2. Fabrication and Test of Experimental Components

(Conf) Figures 8 and 9 show the general make-up of the experimental arm section and the experimental leg section. In each case, an existing outer cover was used since we were principally interested in the functioning of the foam and the inner cover. These covers are described in ref. 1.

(Conf) The experimental components consisted of the outer cover, an inner cover of Mylar film and a liner of knitted nylon fleece. For testing, the outer covers were attached to an MC-3 suit as shown in figure 8, and the fleece liners were attached to knitted underwear of the type ordinarily worn with the MC-3 suit.

(Conf) In the assembly of the fleece liners, the individual sections of the fleece were butted together and a narrow tape of nylon cloth was cemented over the joint. The "Trilok" vapor manifolds were also cemented to the cover, using a latex base cement which also served to seal the edges of the manifold and prevent fraying.

(Conf) The inner covers for the arm and leg sections were made of .0005 inch Mylar film, and were assembled with contact cement. Foot and hand covers were integral parts of the covers.

(Conf) In the case of the hand cover, a dipped neoprene glove, reinforced with nylon cloth was used. The foot cover was merely an extension of the leg cover as shown in figure 9.

(Conf) Since Mylar film is not easily stretched, it is necessary to provide excess material at the knee and elbow of the inner cover to allow free movement. To insure that this excess material was always available, the covers were made considerably longer than necessary and were shortened by bunching the material at the knee and elbow and retaining it with strips of thin rubber, again shown in figure 9.

Figure 8. Experimental Components Attached to MC-3 Suit

(Conf) The foam layers in the outer covers were assembled over forms and then cemented to the inner surface of the restraint layer. The thickness of the layer at each point was determined by measuring the radial distance between the body and the smallest circumscribing circle which could be drawn around the body at that station and taking one fourth this distance as the required foam thickness. The thickness ratio of 1:4 was established by tests of the expansion of unrestrained samples of the foam. Although the method described makes no allowance for the effect of the curvature of the outer cover on the radial expansion of the foam, it was felt that greater accuracy was not justified. This assumption was upheld by the tests of the components.

(Conf) After assembly, both the inner and outer surfaces of the covers were given three coats of Hypalon rubber paint.

(Conf) Three altitude tests of the components were performed, one with the arm section alone and two with both the arm section and the leg section. The tests demonstrated that adequate pressurization could be obtained with the foam and that the Mylar inner cover was feasible. Although as compared with their capstan counterparts, somewhat more effort was required to flex the experimental components, the range of movement was not restricted.

(Conf) Since no negative indications which could be attributed to the design of the components were noted during the tests, the fabrication of the complete suit was undertaken.

D. FABRICATION OF PAPRETEC SUIT

1. General

(Conf) The design of the suit follows very closely the preliminary design previously described. This being the case, the description of the suit which follows will be concerned primarily with features or details of construction which were not touched upon in the earlier section. The experimental arm section described in 2. above and the outer cover of the double leg section described in reference 1, were incorporated into the suit to allow more attention to be given to new problems such as the construction of the shoulder joint. In addition, to make the adjustment of fit somewhat easier, conventional canvas tennis shoes were substituted for the flying boots previously used.

(Conf) Figures 12 through 16 show the major components of the suit which are, respectively, the urinal unit, the liner, the inner cover, and the outer cover. Figure 16 shows also the shoes and the MA-2 helmet which are worn with the suit.

2. Description

(Conf) The outer cover was assembled over a modified plaster cast of the subject as shown in figure 10 in which the cover is seen partially

Figure 9. Inner Covers - Experimental Sections

Figure 10. Outer Cover - Partially Complete

completed. The building form was built up to a circular cross section at all points, except in those areas which were to receive local stiffening.

(Conf) The construction of the body and left arm of the cover is similar to that of the existing double leg section and right arm except that the individual pieces of restraint material are joined with simple lap joints rather than with covered butt joints. This change was made possible by the use of the foam, for which a smooth inner surface in the cover is not required. Lap joints, since they require less material and need not be as carefully fitted, are more economical to manufacture than are covered butt joints.

(Conf) The body and shoulders of the cover were assembled from flat sheets of restraint material, the left elbow and both knees, however, were made of material which had been laid up and cured over curved forms as described in B 2. c. above. The cover over the back of the left hand was laid up directly over the building form and was then removed and curved. Spherical shapes were used over the knees and the outside of the elbow, while on the inside of the elbow, saddle shaped material was used. The angle of intersection between the reinforcing fibers in these formed pieces varies from point to point because of the curvature, but the average is approximately 150° whereas this angle is ordinarily 110° as discussed in reference 1. The angle was increased in this case to make the material more stretchable over the joints of the limbs.

(Conf) As was done in the assembly of the experimental sections, the foam layer of the outer cover was assembled over the building form and then cemented into the cover. Also, in this case, the thickness of foam required was determined by measuring the thickness of build-up on the form and taking one fourth of this as the thickness of the foam.

(Conf) The chest bladder, shown in figure 11 , is made of conventional neoprene coated bladder cloth. A floating stiffener of "Trilok" is installed inside the bladder to keep it from sagging or wrinkling when it is not inflated and to prevent any part of the bladder volume from being pinched off by high local pressure from the foam. The inlet line to the bladder passes through the outer cover on the left side just above the waist. In use, the bladder has an average thickness of approximately one centimeter in the fully inflated condition, and a volume of approximately 1200 cc.

(Conf) The inner cover, shown in figure 15, is a two piece suit made of 0.0005 inch Mylar film. The suit was assembled over a heavy paper form, using contact cement to bond the seams. In the lower half of the cover, a seal is installed at the point where the urinal line passes through the film, and two fittings for the attachment of the external vapor lines are provided. In the upper half, seals are installed at the neck and at each finger. The seal at the waist is formed by folding the excess length of the two halves together. The hand covers are made of vinyl plastic and are reinforced with nylon cloth as necessary to prevent excessive stretching.

(Conf) The urinal unit , figure 12, is made of neoprene rubber by the dipping process described in reference 1. It is held in position, after donning, by the retainer shown in the figure. The top is sealed by folding the end over twice and clamping with a plastic clip. The line from the unit passes through the inner cover and the outer cover and is connected to an external line.

(Conf) Figure 13 shows the nylon fleece liner. As in the experimental components, the liner was assembled by cementing the individual sections together with a covered butt joint using nylon cloth tape and a natural latex based cement. The same cement was used to seal the edges of the "Trilok" manifolds and to attach them to the suit.

(Conf) Figures 13 through 16 show the sequence in which the components of the suit are donned.

(Conf) The sequence for donning the suit and making the final adjustment in fit is as follows:

1. The lower and upper halves of the liner are donned in that order . (Fig. 13)
2. The urinal and hand covers are donned. (Fig. 14)
3. The lower half of the inner cover is donned, and the urinal line is threaded through the seal in the cover.
4. The upper half of the inner cover is donned and the two halves are folded together around the waist (fold up). (Fig. 15)
5. The helmet liner is donned.
6. The external line to be connected to the urinal is threaded through the opening in the outer cover.
7. The outer cover is donned.
8. The urinal lines are connected and excess line is pulled back.
9. The shoes are donned.
10. Helmet cover is donned and tie down adjusted (Fig. 16)
11. External vapor lines and oxygen lines are connected.

(Conf) Final adjustment of the suit will be made in the altitude chamber at the equivalent of 35000 ft. altitude.

E. CONCLUSIONS

(Conf) The performance of the experimental components clearly demonstrated that passive mechanical pressurization of a space worker's garment by an expandable foam is feasible, and that the basic concepts upon which their design was based are sound. In general, the components, and the suit, because of their loose fit, and their flexibility, are relatively easy to don and doff although improvement in this area is required. During test, the experimental parts were reported, by the test subject, to be comfortable. Compared with their capstan counterparts, somewhat more effort was required to flex or extend the arm section and the leg section, but the range of movement was not

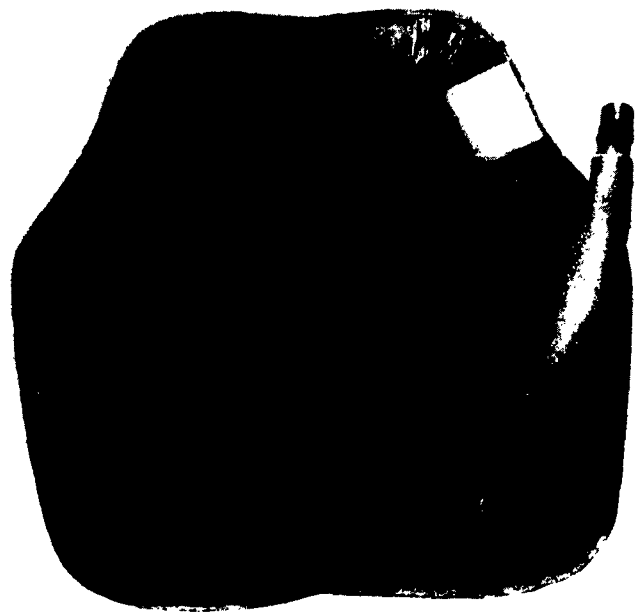


Figure 11. Chest Bladder

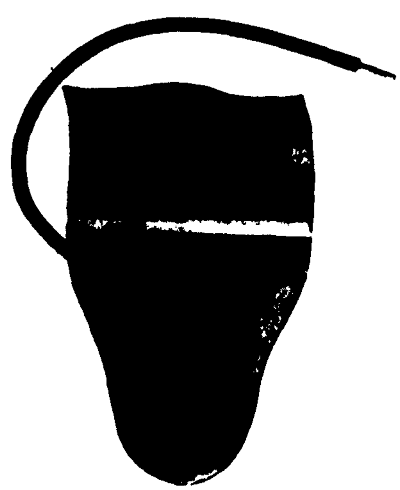


Figure 12. Urinal Unit

Figure 13. Liner - PAPRETEC Suit
(First Step in Donning Sequence)

Figure 14. Urinal and Hand Covers

Figure 15. Inner Cover

Figure 16. Outer Cover and Helmet (Complete Suit)

Figure 17. Complete Suit

noticeably restricted. On the basis of the tests performed and the experience gained during the assembly of the experimental parts and the suit, it appears that while certain changes in detail design are desirable, no major change in the basic design is required.

F. RECOMMENDATIONS

(Conf) In view of our findings thus far, we feel that further development of the PAPRETEC concept along the lines already established would be very rewarding. The next phase of the program should be directed primarily toward the refinement of the basic design and improvements of the materials used in the construction of the suit, as contrasted with the exploratory nature of the preceding work.

(Conf) In the area of design improvement, the emphasis should be on improving joint mobility. Because of the complexity of the problem, the necessary improvement will probably be achieved only through a relatively detailed study of the problem, but there are several potentially successful lines of attack for such a study, all of which are compatible with the general design. For example, a modified version of the restrained bellows joint might be suitable for the knee and elbow. The restraining elements already exist in the zipper and loop tape which follow the neutral lines of the limbs.

(Conf) It was pointed out in section I , that under normal conditions in a spacecraft cabin, the foam will not fill completely the space between the restraint layer and the body, and that the resulting space between the foam and the body would allow air to be circulated through the suit as an alternate method of thermal control. Since the incorporation of this ventilating feature into the present design would result in a more versatile and adaptable suit, it is recommended that future work include the development of a ventilating garment for the PAPRETEC suit. The ventilating garment, which would replace the present inner cover, would be essentially an air distribution system with provisions for bleeding into the space occupied by the fleece to remove water vapor. Under space conditions, or when evaporative cooling is used in the cabin, the ventilating garment would function as a vapor barrier.

(Conf) In addition to such design changes as may result from the study of the joint mobility problem, it is recommended that the coverage of the restraint garment be extended to include the feet to eliminate the shoes now used. Conventional shoes, because of their general design, are difficult to adjust so that uniform counter-pressure is applied over the foot and ankle.

(Conf) In the area of materials improvement, the work will depend to some extent upon the course of the mobility study, but two specific recommendations can be made regarding the foam and the outer cover material.

(Conf) In the case of the foam, work should continue on the development of improved coatings to prevent the diffusion of gas from the cells, and on the improvement of the foam processing methods to increase the reproducibility of results.

(Conf) In the case of the outer cover material, the shaped material described in section II D, should be investigated further. To support this investigation, it will first be necessary to work out methods of producing the shaped material in practical sizes and quantities.

H. REFERENCES

1. Mauch, H. and Marcum, A. A Study and Design of Materials and Techniques For High Altitude Protective Assemblies. MRL-TDR 62-13, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, Feb. 1962

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The purpose of the work described in this report was the investigation of integrated passive techniques for pressurization and thermal control in a space worker's garment. The specific goal of this work was the development and fabrication of a complete laboratory

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2. Temperature Control
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model space worker's garment, based upon passive techniques, with which the problems of passive physiological protection could be further explored. The suit design which developed is based upon mechanical pressurization using an expandable closed cell foam material as the pressurizing medium, and upon thermal control by the controlled evaporation of sweat at reduced pressures. Two experimental components, an arm section, and a single leg section, were assembled and tested to provide data for the design of the suit. The results of the investigation indicate that the PAPRETEC (PAssive PREssurization and TEmperature Control) concept is feasible and that further development of the suit should be undertaken.

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